

**NON-VOLATILE MEMORY AND METHOD  
WITH BIT LINE TO BIT LINE COUPLED COMPENSATION**

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**FIELD OF THE INVENTION**

[0001] This invention relates generally to non-volatile semiconductor memory such as electrically erasable programmable read-only memory (EEPROM) and flash EEPROM, and specifically ones having improved programming and sensing circuits for a page of contiguous row of charge storage units.

**BACKGROUND OF THE INVENTION**

[0002] Solid-state memory capable of non-volatile storage of charge, particularly in the form of EEPROM and flash EEPROM packaged as a small form factor card, has recently become the storage of choice in a variety of mobile and handheld devices, notably information appliances and consumer electronics products. Unlike RAM (random access memory) that is also solid-state memory, flash memory is non-volatile, retaining its stored data even after power is turned off. In spite of the higher cost, flash memory is increasingly being used in mass storage applications. Conventional mass storage, based on rotating magnetic medium such as hard drives and floppy disks, is unsuitable for the mobile and handheld environment. This is because disk drives tend to be bulky, are prone to mechanical failure and have high latency and high power requirements. These undesirable attributes make disk-based storage impractical in most mobile and portable applications. On the other hand, flash memory, both embedded and in the form of a removable card is ideally suited in the mobile and handheld environment because of its small size, low power consumption, high speed and high reliability features.

[0003] EEPROM and electrically programmable read-only memory (EPROM) are non-volatile memory that can be erased and have new data written or “programmed” into their memory cells. Both utilize a floating (unconnected) conductive gate, in a field effect transistor structure, positioned over a channel region in a semiconductor substrate, between source and drain regions. A control gate is then provided over the floating gate. The threshold voltage characteristic of the transistor is controlled by the amount of charge that is retained on the floating gate. That is, for a given level of charge on the floating gate, there is a corresponding voltage (threshold) that must be applied to the control gate before the transistor is turned “on” to permit conduction between its source and drain regions.

[0004] The floating gate can hold a range of charges and therefore can be programmed to any threshold voltage level within a threshold voltage window. The size of the threshold voltage window is delimited by the minimum and maximum threshold levels of the device, which in turn correspond to the range of the charges that can be programmed onto the floating gate. The threshold window generally depends on the memory device’s characteristics, operating conditions and history. Each distinct, resolvable threshold voltage level range within the window may, in principle, be used to designate a definite memory state of the cell.

[0005] The transistor serving as a memory cell is typically programmed to a “programmed” state by one of two mechanisms. In “hot electron injection,” a high voltage applied to the drain accelerates electrons across the substrate channel region. At the same time, a high voltage applied to the control gate pulls the hot electrons through a thin gate dielectric onto the floating gate. In “tunneling injection,” a high voltage is applied to the control gate relative to the substrate. In this way, electrons are pulled from the substrate to the intervening floating gate.

[0006] The memory device may be erased by a number of mechanisms. For EPROM, the memory is bulk erasable by removing the charge from the floating gate by ultraviolet radiation. For EEPROM, a memory cell is electrically erasable, by applying a high voltage to the substrate relative to the control gate so as to induce electrons in the floating gate to tunnel through a thin oxide to the substrate channel region (i.e., Fowler-Nordheim tunneling). Typically, the EEPROM is erasable byte by byte. For flash EEPROM, the memory is electrically erasable either all at once or one or more blocks at

a time, where a block may consist of 512 bytes or more of memory.

**[0007]** The memory devices typically comprise one or more memory chips that may be mounted on a card. Each memory chip comprises an array of memory cells supported by peripheral circuits such as decoders and erase, write and read circuits. The more sophisticated memory devices also come with a controller that performs intelligent and higher level memory operations and interfacing. There are many commercially successful non-volatile solid-state memory devices being used today. These memory devices may employ different types of memory cells, each type having one or more charge storage unit.

**[0008]** FIG. 1 illustrates schematically a non-volatile memory cell in the form of an EEPROM cell. It has a charge storage unit in the form of a floating gate. An electrically erasable and programmable read-only memory (EEPROM) has a similar structure to EPROM, but additionally provides a mechanism for loading and removing charge electrically from its floating gate upon application of proper voltages without the need for exposure to UV radiation. Examples of such cells and methods of manufacturing them are given in United States Patent No. 5,595,924.

**[0009]** FIG. 2 illustrates schematically a string of charge storage units organized into a NAND cell or string. A NAND cell 50 consists of a series of memory transistors M1, M2, ... Mn ( $n=4, 8, 16$  or higher) daisy-chained by their sources and drains. A pair of select transistors S1, S2 controls the memory transistors chain's connection to the external via the NAND cell's source terminal 54 and drain terminal 56. In a memory array, when the source select transistor S1 is turned on by the signal SGS, the source terminal is coupled to a source line. Similarly, when the drain select transistor S2 is turned on by the signal SGD, the drain terminal of the NAND cell is coupled to a bit line of the memory array. Each memory transistor in the chain has a charge storage unit to store a given amount of charge so as to represent an intended memory state. Between each source and drain of each memory transistor is a channel region. Voltage on a control gate on each memory transistor, such as 60, 62, ..., 64 controls current conduction in the channel of the memory transistors M1, M2, ..., Mn respectively. The select transistors S1, S2 provides control access to the NAND cell via its source terminal 54 and drain terminal 56 respectively and each is turned on by appropriate voltage to its control gate.

[0010] When an addressed memory transistor within a NAND cell is read or verified during programming, its control gate is supplied with an appropriate reference voltage. At the same time, the rest of the non-addressed memory transistors in the NAND cell 50 are fully turned on by application of a sufficient voltage  $V_{PASS}$  on their control gates. In this way, a conductive path is effectively created from the source of the individual memory transistor to the source terminal 54 of the NAND cell and likewise for the drain of the individual memory transistor to the drain terminal 56 of the cell. Similarly during programming, the memory transistor to be programmed has its control gate supplied with a programming voltage  $V_{PGM}$ , while the other memory transistors in string have their control gate supplied with the pass voltage  $V_{PASS}$ . Memory devices with such NAND cell structures are described in United States Patent Nos. 5,570,315, 5,903,495 and 6,046,935.

[0011] Another similar non-volatile memory has each of its charge storage units in the form of a dielectric layer. Instead of the conductive floating gate elements described earlier, a dielectric layer is used. Such memory devices utilizing dielectric storage element have been described by Eitan et al., "NROM: A Novel Localized Trapping, 2-Bit Non-volatile Memory Cell," IEEE Electron Device Letters, vol. 21, no. 11, November 2000, pp. 543-545. An ONO dielectric layer extends across the channel between source and drain diffusions. The charge for one data bit is localized in the dielectric layer adjacent to the drain, and the charge for the other data bit is localized in the dielectric layer adjacent to the source. For example, United States Patents Nos. 5,768,192 and 6,011,725 disclose a non-volatile memory cell having a trapping dielectric sandwiched between two silicon dioxide layers. Multi-state data storage is implemented by separately reading the binary states of the spatially separated charge storage regions within the dielectric.

#### MEMORY ARRAY

[0012] A memory device typically comprises of a two-dimensional array of memory cells arranged in rows and columns and addressable by word lines and bit lines.

[0013] **FIG. 3** illustrates an example of an array of NAND cells, such as that shown in **FIG. 2**. Along each column of NAND cells, a bit line 36 is coupled to the drain terminal 56 of each NAND cell. Along each row of NAND cells, a source line 34 may connect all

their source terminals 54. Also the control gates 60, ..., 64 of the NAND cells along a row are connected to a series of corresponding word lines. An entire row of NAND cells can be addressed by turning on the pair of select transistors (see FIG. 2) with appropriate voltages on their control gates SGD and SGS via the connected word lines. When a memory transistor within the chain of a NAND cell is being read, the remaining memory transistors in the chain are turned on hard via their associated word lines so that the current flowing through the chain is essentially dependent upon the level of charge stored in the cell being read. An example of a NAND architecture array and its operation as part of a memory system is found in United States patents nos. 5,570,315, 5,774,397 and 6,046,935.

#### BLOCK ERASE

[0014] Programming of charge storage memory devices can only result in adding more charge to its charge storage elements. Therefore, prior to a program operation, existing charge in a charge storage element must be removed (or erased). Erase circuits (not shown) are provided to erase one or more blocks of memory cells. A non-volatile memory such as EEPROM is referred to as a "Flash" EEPROM when an entire array of cells, or significant groups of cells of the array, is electrically erased together (i.e., in a flash). Once erased, the group of cells can then be reprogrammed. The group of cells erasable together may consist of one or more addressable erase unit. The erase unit or block typically stores one or more pages of data, the page being the unit of programming and reading, although more than one page may be programmed or read in a single operation. Each page typically stores one or more erase blocks of data, the size of the erase block being defined by the host system. An example is an erase block of 512 bytes of user data, following a standard established with magnetic disk drives, plus some number of bytes of overhead information about the user data and/or the block in which it is stored. In other systems, the erase block size can be much larger than 512 bytes.

#### READ/WRITE CIRCUITS

[0015] In the usual two-state EEPROM cell, at least one current breakpoint level is established so as to partition the conduction window into two regions. When a cell is read by applying predetermined, fixed voltages, its source/drain current is resolved into a memory state by comparing with the breakpoint level (or reference current  $I_{REF}$ ). If the

current read is higher than that of the breakpoint level or  $I_{REF}$ , the cell is determined to be in one logical state (e.g., a "zero" state). On the other hand, if the current is less than that of the breakpoint level, the cell is determined to be in the other logical state (e.g., a "one" state). Thus, such a two-state cell stores one bit of digital information. A reference current source, which may be externally programmable, is often provided as part of a memory system to generate the breakpoint level current.

[0016] In order to increase memory capacity, flash EEPROM devices are being fabricated with higher and higher density as the state of the semiconductor technology advances. Another method for increasing storage capacity is to have each memory cell store more than two states.

[0017] For a multi-state or multi-level EEPROM memory cell, the conduction window is partitioned into more than two regions by more than one breakpoint such that each cell is capable of storing more than one bit of data. The information that a given EEPROM array can store is thus increased with the number of states that each cell can store. EEPROM or flash EEPROM with multi-state or multi-level memory cells have been described in U.S. Patent No. 5,172,338.

[0018] In practice, the memory state of a cell is usually read by sensing the conduction current across the source and drain electrodes of the cell when a reference voltage is applied to the control gate. Thus, for each given charge on the floating gate of a cell, a corresponding conduction current with respect to a fixed reference control gate voltage may be detected. Similarly, the range of charge programmable onto the floating gate defines a corresponding threshold voltage window or a corresponding conduction current window.

[0019] Alternatively, instead of detecting the conduction current among a partitioned current window, it is possible to set the threshold voltage for a given memory state under test at the control gate and detect if the conduction current is lower or higher than a threshold current. In one implementation, the detection of the conduction current relative to a threshold current is accomplished by examining the rate the conduction current is discharging through the capacitance of the bit line.

## FACTORS AFFECTING READ/WRITE PERFORMANCE AND ACCURACY

[0020] In order to improve read and program performance, multiple charge storage elements or memory transistors in an array are read or programmed in parallel. Thus, a logical “page” of memory elements are read or programmed together. In existing memory architectures, a row typically contains several interleaved pages. All memory elements of a page will be read or programmed together. The column decoder will selectively connect each one of the interleaved pages to a corresponding number of read/write modules. For example, in one implementation, the memory array is designed to have a page size of 532 bytes (512 bytes plus 20 bytes of overheads). If each column contains a drain bit line and there are two interleaved pages per row, this amounts to 8512 columns with each page being associated with 4256 columns. There will be 4256 sense modules connectable to read or write in parallel either all the even bit lines or the odd bit lines. In this way, a page of 4256 bits (i.e., 532 bytes) of data in parallel are read from or programmed into the page of memory elements. The read/write modules forming the read/write circuits 170 can be arranged into various architectures.

[0021] As mentioned before, conventional memory devices improve read/write operations by operating in a massively parallel manner. This approach improves performances but does have repercussions on the accuracy of read and write operations.

[0022] Another issue has to do with bit line to bit line coupling or crosstalk. This problem becomes more acute with parallel sensing of closely spaced bit lines. A conventional solution to avoid bit line to bit line crosstalk is to sense either all even or all odd bit lines at a time while grounding the other bit lines. This architecture of a row consisting of two interleaved pages will help to avoid bit line crosstalk as well as to alleviate the problem of densely fitting the page of read/write circuits. A page decoder is used to multiplex the set of read/write modules to either the even page or the odd page. In this way, whenever one set of bit lines are being read or programmed, the interleaving set can be grounded to eliminate crosstalk between odd and even bit lines, but not between odd lines or even lines.

[0023] However, the interleaving page architecture is disadvantageous in at least three respects. First, it requires additional multiplexing circuitry. Secondly, it is slow in performance. To finish read or program of memory cells connected by a word line or in

a row, two read or two program operations are required. Thirdly, it is also not optimum in addressing other disturb effects such as field coupling between neighboring charge storage elements at the floating gate level when the two neighbors are programmed at different times, such as separately in odd and even pages.

**[0024]** The problem of neighboring field coupling becomes more pronounced with ever closer spacing between memory transistors. In a memory transistor, a charge storage unit is sandwiched between a channel region and a control gate. The current that flows in the channel region is a function of the resultant electric field contributed by the field at the control gate and the charge storage unit. With ever increasing density, memory transistors are formed closer and closer together. The field from neighboring charge elements then becomes a significant contributor to the resultant field of an affected cell. The neighboring field depends on the charge programmed into the charge storage unit of the neighbors. This perturbing field is dynamic in nature as it changes with the programmed states of the neighbors. Thus, an affected cell may read differently at different times depending on the changing states of the neighbors.

**[0025]** The conventional architecture of interleaving page exacerbates the error caused by neighboring charge storage unit coupling. Since the even page and the odd page are programmed and read independently of each other, a page may be programmed under one set of conditions but read back under an entirely different set of conditions, depending on what has happened to the intervening page in the meantime. The read errors will become more severe with increasing density, requiring a more accurate read operation and wider partitioning of the threshold window for multi-state implementation. Performance will suffer and the potential capacity in a multi-state implementation is limited.

**[0026]** United States Patent Applications, Serial Nos. 10/254483 and 10/254290 filed on September 24, 2002, disclose a memory architecture in which a page of contiguous memory storage units are programmed or read in parallel. As programming is performed on a page of contiguous memory storage units, during the process those memory storage units that have been programmed to their targeted state will be program-inhibited or locked out from further programming. In a preferred scheme, the memory storage units are locked out by floating their channels and boosting the voltage there to inhibit programming. This boosted voltage creates a significant perturbation on an adjacent



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storage unit still under programming.

**[0027]** Therefore there is a general need for high performance and high capacity non-volatile memory. In particular, there is a need to have a high capacity non-volatile memory with improved read and program performance that effectively manages the aforementioned problems.

## SUMMARY OF INVENTION

**[0028]** These needs for a high capacity and high performance non-volatile memory device are met by having a large page of read/write circuits to read and write a corresponding page of memory cells in parallel. In particular, disturbance effects inherent in high-density chip integration that may introduce errors into reading and programming are either eliminated or minimized.

**[0029]** When programming a contiguous page of storage units, every time a storage unit has reached its targeted state and is program-inhibited or locked out from further programming, it creates a perturbation on an adjacent storage unit still under programming. The present invention provides as part of a programming circuit and method in which an offset to the perturbation is added to the adjacent storage unit still under programming. The offset is added by a controlled coupling between the adjacent bit lines of the program-inhibited storage unit and the still under programming storage unit. In this way, an error inherent in programming in parallel high-density memory storage units is eliminated or minimized.

**[0030]** According to a preferred embodiment, the storage unit is put into program-inhibit mode by floating its channel and boosting its voltage to a program inhibiting voltage. This entails raising its bit line voltage to enable floating. The adjacent bit line of the storage unit still under programming is floated for some portion of this voltage rise in order to couple a predetermined offset into its own bit line. In this way, the perturbation by the program-inhibited storage unit on the still to be programming storage unit is automatically tracked and compensated by the offset under controlled bit line to bit line coupling.

**[0031]** According to another embodiment, the channel boosting for program inhibition is performed before the coupling of the offset.

**[0032]** According to another aspect of the invention, the bit line of a storage unit still under programming is set to a potential that maximizes programming efficiency whenever both of its adjacent neighboring storage units are also still under programming. In the preferred embodiment, the bit line is set to the ground potential. This avoids any coupling from neighboring storage units who in turn may have their voltages boosted by adjacent storage unit under program inhibition.

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**[0033]** Additional features and advantages of the present invention will be understood from the following description of its preferred embodiments, which description should be taken in conjunction with the accompanying drawings.

## **BRIEF DESCRIPTION OF THE DRAWINGS**

**[0034] FIG. 1** illustrates schematically a non-volatile memory cell in the form of an EEPROM cell.

**[0035] FIG. 2** illustrates schematically a string of charge storage units organized into a NAND cell or string.

**[0036] FIG. 3** illustrates an example of an array of NAND cells, such as that shown in **FIG. 2**.

**[0037] FIG. 4A** illustrates schematically a memory device having read/write circuits for reading and programming a page of memory cells in parallel, according to one embodiment of the present invention.

**[0038] FIG. 4B** illustrates a preferred arrangement of the memory device shown in **FIG. 4A**.

**[0039] FIG. 5A** illustrates a sectional perspective view of a memory transistor along the direction 5A-5A shown in **FIG. 2** and the equivalent capacitance between the charge storage unit and the word line and between the charge unit and the channel.

**[0040] FIG. 5B** illustrates schematically the capacitive coupling of the memory transistor shown in **FIG. 5A**, showing in particular the voltage at the charge storage unit due to the voltage at the channel and the voltage at the word line.

**[0041] FIG. 6A** illustrates a sectional perspective view of the array of NAND cells shown in **FIG. 3** for the case when two adjacent memory transistors are both in programming mode.

**[0042] FIG. 6B** illustrates a sectional perspective view of the NAND array similar to **FIG. 6A**, except one of the adjacent memory transistors is in program inhibit mode.

**[0043] FIG. 7** schematically represents the capacitive coupling between the two bit lines by a capacitor.

**[0044] FIGs. 8(A)-8(G)** are timing diagrams illustrating the voltage compensation scheme by capacitive bit line-bit line coupling during program operations, according to a

first embodiment of the invention.

**[0045] FIGs. 9(A)-9(G)** are timing diagrams illustrating the voltage compensation scheme by capacitive bit line-bit line coupling during program operations, according to a second embodiment of the invention.

**[0046] FIG. 10** is a flow diagram showing a method of programming a page of contiguous memory storage units while minimizing the coupling errors due to individual memory transistors among them being program inhibited or locked out, according to one preferred embodiment.

**[0047] FIG. 11** is a flow diagram showing a method of programming a page of contiguous memory storage units while minimizing the coupling errors due to individual memory transistors among them being program inhibited or locked out, according to another preferred embodiment.

**[0048] FIG. 12** illustrates a preferred sense module implementing the various aspects of the present invention.

**[0049] FIG. 13** illustrates a programming configuration along a row of NAND chains where a second order error may still occur.

**[0050] FIG. 14** illustrates a sense module configuration in which each sense module also senses the INV signal of its neighbors.

**[0051] FIG. 15** illustrates an alternative implementation in which the signal indicating whether a neighbor is in program or program inhibit mode is derived directly from the state of the neighbor's bit line.

## DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

### ALL BIT LINE PROGRAMMING

[0052] The sense module 380 shown in **FIG. 4A**, **FIG. 4B** and **FIG. 12** is preferably implemented in a memory architecture configured to perform all-bit-line sensing. In other words, contiguous memory cells in a row are each connectable to a sense module to perform sensing in parallel. Such a memory architecture is also disclosed in co-pending and commonly assigned United States Patent Application Serial No. 10/254,483 filed by Cernea et al., on September 24, 2002 entitled, "Highly Compact Non-Volatile Memory And Method Thereof." The entire disclosure of said patent application is hereby incorporated herein by reference.

[0053] As described earlier, the number of memory cells in a "page" that are programmed or read simultaneously may vary according to the size of data sent or requested by a host system. Thus, there are several ways to program the memory cells coupled to a single word line, such as (1) programming even bit lines and odd bit lines separately, which may comprise upper page programming and lower page programming, (2) programming all the bit lines ("all-bit-line programming"), or (3) programming all the bit lines in a left or right page separately, which may comprise right page programming and a left page.

[0054] **FIG. 4A** illustrates schematically a memory device having read/write circuits for reading and programming a page of memory cells in parallel, according to one embodiment of the present invention. The memory device includes a two-dimensional array of memory cells 300, control circuitry 310, and read/write circuits 370. The memory array 300 is addressable by word lines via a row decoder 330 and by bit lines via a column decoder 360. The read/write circuits 370 include multiple sense modules 380 and allow a page of memory cells to be read or programmed in parallel.

[0055] In the present invention, the page of memory cells to be read or programmed in parallel is preferably a row of contiguous memory storage cells or storage units. In other embodiments, the page is a segment of a row of contiguous memory storage cells or storage units.

[0056] The control circuitry 310 cooperates with the read/write circuits 370 to perform

memory operations on the memory array 300. The control circuitry 310 includes a state machine 312, an on-chip address decoder 314 and a power control module 316. The state machine 312 provides chip level control of memory operations. The on-chip address decoder 314 provides an address interface between that used by the host or a memory controller to the hardware address used by the decoders 330 and 370. The power control module 316 controls the power and voltages supplied to the word lines and bit lines during memory operations.

[0057] **FIG. 4B** illustrates a preferred arrangement of the memory device shown in **FIG. 4A**. Access to the memory array 300 by the various peripheral circuits is implemented in a symmetric fashion, on opposite sides of the array so that the densities of access lines and circuitry on each side are reduced in half. Thus, the row decoder is split into row decoders 330A and 330B and the column decoder into column decoders 360A and 360B. Similarly, the read/write circuits are split into read/write circuits 370A connecting to bit lines from the bottom and read/write circuits 370B connecting to bit lines from the top of the array 300. In this way, the density of the read/write modules, and therefore that of the sense modules 380, is essentially reduced by one half.

#### BOOSTED VOLTAGE ON CHANNEL AND CHARGE STORAGE UNIT

[0058] An error inherent in high-density integrated circuit, non-volatile memory device is due to the coupling of neighboring charge storage units and channel regions. If the channel region and charge storage unit of one memory storage unit is boosted relative to an adjacent one, it will cause a perturbation on the charge storage unit of the adjacent unit. This effect is more pronounced when the memory storage units being programmed in parallel are densely packed or inadequately shielded.

[0059] **FIG. 5A** illustrates a sectional perspective view of a memory transistor along the direction 5A-5A shown in **FIG. 2** and the equivalent capacitance between the charge storage unit and the word line and between the charge unit and the channel. The memory transistor M1 has the control gate 60 being formed as part of a word line running along a row of the NAND array 100 (see **FIG. 3**). In this view, the drain is coming out of the page of **FIG. 5A** and the source is at the back, defining a channel region 80 in between. A charge storage unit 70 is interposed between the control gate 60 and the channel 80 and is insulated from both of them by layers of dielectric material. The electrical

coupling between the charge storage unit 70 and the control gate 60 can be modeled by an equivalent capacitor  $C_{WF}$ . Similarly, the coupling between the charge storage unit 70 with the channel 80 can be modeled by an equivalent capacitor  $C_{FC}$ .

[0060] **FIG. 5B** illustrates schematically the capacitive coupling of the memory transistor shown in **FIG. 5A**, showing in particular the voltage at the charge storage unit due to the voltage at the channel and the voltage at the word line. If the charge storage unit 70 is storing  $Q$  amount of charge, then  $C_{WF}$  and  $C_{FC}$  both hold the same charge. The voltage at the charge storage unit 70,  $V_{CS} = (C_{WF} V_W + C_{WF} V_C) / (C_{WF} + C_{FC})$ . It can be readily seen that generally the voltage of the charge storage unit increases with increasing voltage at the channel and/or at the word line. As will be described in the next section, when a memory transistor such as M1 is placed in a program inhibit mode, the channel voltage is boosted to a high voltage. Therefore this will also result in a boosted voltage at the charge storage unit. The combination of boosted voltages at the channel 80 and the charge storage unit 70 will have a perturbation effect on adjacent memory transistors engaged in a programming mode.

#### PROGRAM OVERTHROTT DUE TO AN ADJACENT UNIT IN BOOSTED (PROGRAM INHIBIT) STATE

[0061] **FIG. 6A** illustrates a sectional perspective view of the array of NAND cells shown in **FIG. 3** for the case when two adjacent memory transistors are both in programming mode. For example, **FIG. 6A** may represent three adjacent memory transistors, such as M1-1, M1-2 and M1-3 respectively belonging to the NAND strings 50-1, 50-2 and 50-3, along a row sharing the same word line 60. The NAND strings 50-1, 50-2 and 50-3 respectively have bit lines 36-1, 36-2 and 36-3 connectable to them. The memory transistors M1-1, M1-2 and M1-3 have corresponding charge storage units 70-1, 70-2 and 70-3 and channels 80-1, 80-2 and 80-3.

[0062] With increasing density of the memory array, the memory transistors are formed closer together and their effect on each other becomes more significant. For example, the threshold voltage of the memory transistor M1-2 is dependent on the voltage on its charge storage unit 70-2. Because of the close proximity to its adjacent neighbors M1-1 and M1-3, the voltages at the channels and charge storage units of M1-1 and M1-3 can affect the voltage on the charge storage unit of M1-2. For example, the charge storage



unit 70-2 may be regarded as coupled to its adjacent charge storage units 70-1 and 70-3 respectively by equivalent capacitors  $C_{12}$  and  $C_{23}$ . Similarly, the charge storage unit 70-2 may be regarded as coupled to its adjacent channels 80-1 and 80-3 respectively by equivalent capacitors  $C'_{12}$  and  $C'_{23}$ . The closer the spacing between the memory transistors, the more will the coupling be between them.

**[0063] FIG. 6A** illustrates the case when two adjacent memory transistors M1-2 and M1-1 are both in programming mode. Focusing on the effect on M1-2 due to M1-1, there is little variation due to the word line and bit line voltages since they are the same for M1-2 and M1-1. The channel voltages are also similar. The only variation seen by the charge storage unit 70-2 is due to that of the charge storage unit 70-1, which is mainly a function of the charge it is holding or its data representation. For example, the voltage on the charge storage units of M1-1 and M1-2 may be about 1 to 2V. The perturbation due to this type of perturbation is typically accounted for by allowing sufficient margin between two different memory states.

**[0064] FIG. 6B** illustrates a sectional perspective view of the NAND array similar to **FIG. 6A**, except one of the adjacent memory transistors is in program inhibit mode. In this case, M1-2 is being programmed while M1-1 is inhibited from further programming. The word line voltage remains the same for both but the voltage on the bit line 36-1 of M1-1 has now changed to  $V_{DD}$ , which is a predetermined system voltage, e.g.,  $\sim 2.5V$ . This effectively turns off the select transistor S2 (see **FIG. 2**), disconnects the NAND chain 50-1 from its bit line 36-1, and floats the channel 80-1 of M1-1 so that it can be capacitively boosted up to a high voltage when a high voltage appears on the word line 60. For example, in this way, the channel 80-1 of M1-1 can be boosted to 10V. Boosting up the channel voltage will effectively reduce the potential difference between the channel and the charge storage unit, thereby discouraging pulling electrons from the channel to the charge storage unit to effect programming.

**[0065]** In view of the discussion in connection with **FIG. 5B** earlier, a boosted channel will cause a boosted charge storage unit. For example, when the memory transistor M1-1 is in program inhibit mode, it can result in a voltage boost at the channel 80-1 of about 10V and a voltage boost at the charge storage unit 70-1 from 2V to 8V. This can significantly perturb a neighboring memory transistor (e.g., M1-2) to be programmed. The charge storage unit 70-2 of M1-2 may for example have its voltage boosted by  $\Delta V_2$

~ 0.2V. This is due to its charge storage unit 70-2 being capacitively coupled, e.g.,  $C_{12}$  and  $C'_{12}$  respectively, to the charge storage unit 70-1 and the channel 80-1 of the boosted (program inhibited) memory transistor M1-1. Typically, the memory transistor's threshold voltage is programmed in steps of between 0.8V to about 0.1V or less, this will results in M1-2 being erroneously programmed to a higher threshold value than expected.

[0066] So far the discussion has focused on the effect on the memory transistor M1-2 due to M1-1. If M1-3 is also in program inhibit mode, its boosted voltage will couple in similar manner to contribute to the boosting of the voltage on the charge storage unit 70-2 of M1-2. In the worst case where the memory transistor M1-2 is in program mode while its neighbors M1-1 and M1-3 on either side are being locked out (program inhibited) from further programming, the perturbation on the charge storage unit 70-2 of M1-2 can be as high as 0.2V. To M1-2 under programming, this effect is equivalent to the programming voltage on its control gate being increased by as high as 0.4V. This can cause over-programming to the wrong state under some circumstances. For example, the memory cell may have its threshold window partitioned with a separation of about .3V and the programming pulse step is incremented by about 0.1V each time so that it typically takes more than one pulse to traverse each partition. A current programming pulse step may bring M1-2 to just below the threshold region designating the desired programmed state. At the same time the current pulse step may program M1-1 and M1-3 to their final state so that they are locked out from further programming by entering into program inhibit mode. Thus, in the next programming pulse step, M1-2 is suddenly subjected to a large programming step of as much as 0.5V. This will likely make M1-2 over shoot the desired threshold region and be programmed erroneously into the next memory state.

#### AUTO-COMPENSATION OF DISTURB DUE TO NEIGHBOR'S VOLTAGE BOOST

[0067] **FIG. 7** illustrates the bit-line to bit-line coupling mechanism for compensating the perturbation from an adjacent memory transistor in program inhibit mode, according to a preferred embodiment of the present invention.

[0068] Using the same example as in **FIG. 6B**, the memory transistor M1-2 is being programmed while the adjacent M1-1 is inhibited from further programming. As the description above indicates, the boosted channel 80-1 and charge storage unit 70-1 of

M1-1 will result in the voltage at the charge storage unit 70-2 of M1-2 boosted by  $\Delta V_2$ , thereby resulting in a programming error.

**[0069]** According to a preferred embodiment, the perturbing  $\Delta V_2$  at the charge storage unit 70-2 is compensated by introducing a similar amount on the bit line 36-2. This bit line compensated voltage will be passed to the channel so that the net change in the potential difference between the charge storage unit 70-2 and the channel 80-2 will be effectively zero. In this way, any errors in the threshold voltage will be canceled out. An auto-compensating scheme is employed. Any time a memory transistor such as M1-1 enters into a program inhibit mode, its bit line 36-1 changes from a voltage of 0V to  $V_{DD}$  so that its channel can be enabled for floating to achieve program inhibited boosting. This rise in bit line voltage can be used to boost the voltage of a neighboring bit line such as the bit line 36-2 by capacitive coupling between the two bit lines.

**[0070]** FIG. 7 schematically represents the capacitive coupling between the two bit lines 36-1 and 36-2 by a capacitor  $C_{BL12}$ . A similar capacitor  $C_{BL23}$  exists between the bit lines 36-2 and 36-3. When the bit line 36-2 for the memory transistor M1-2 is floated and the voltage on the neighboring bit line 36-1 is raised by  $\Delta V_1$ , a portion of the raised voltage  $\alpha \Delta V_1$  (where  $\alpha$  is a coupling constant and has been estimated in some instance to be  $\sim 40\%$ ) will be coupled via the capacitor  $C_{BL12}$  to the bit line 36-2. This coupled voltage will act as the offset for the erroneous  $\Delta V_2$  at its charge storage unit 70-2. In general,  $\Delta V_1$  is a predetermined voltage such that the coupled portion  $\alpha \Delta V_1 \sim \Delta V_2$ . As the bit line 36-1 (for the program lockout or inhibited memory transistor M1-1) changes from 0V to  $V_{DD}$ , the bit line 36-2 (for the memory transistor M1-2 to be programmed) is floated to couple in a predetermined  $\alpha \Delta V_1$ . Preferably, the bit line 36-2 is set to 0V (not floated) during a first period where the voltage of the bit line 36-1 rises from 0V to  $V_{DD} - \Delta V_1$ . Then, in a second period, where the bit line 36-1 rises by the last  $\Delta V_1$ , the bit line 36-2 is floated to couple in  $\alpha \Delta V_1 \sim \Delta V_2$ . In this way, for a memory transistor M1-2 (in NAND chain 50-2) under programming, its bit line 36-2 voltage is compensated by an offset equal to  $\Delta V_2$  whenever one of its neighboring transistor (e.g., M1-1 in NAND chain 50-1) enters into a program inhibit mode.

**[0071]** FIGs. 8(A)-8(G) are timing diagrams illustrating the voltage compensation scheme by capacitive bit line-bit line coupling during program operations, according to a

first embodiment of the invention. The voltages shown are applied to various word lines and bit lines of the memory array, for NAND chains under programming and program inhibition (see also **FIG. 2** and **FIG. 3**). The program operation can be grouped into a Bit Lines Precharge Phase, a Program Phase and a Discharge Phase.

In the Bit Lines Precharge Phase:

**[0072]** (1) The source select transistor is turned off by SGS at 0V (**FIG. 8(A)**) while the drain select transistor is turned on by SGD going high to  $V_{SG}$  (**FIG. 8(B)**), thereby allowing a bit line to access a NAND chain.

**[0073]** (2) The bit line voltage of a program inhibited NAND chain is allowed to rise (in the first of a two-step rise) to a predetermined voltage given by  $V_{DD} - \Delta V_1$  (**FIG. 8(F)**). At the same time, the bit line voltage of a programming NAND chain is actively pulled down to 0V (**FIG. 8(G)**).

**[0074]** (3) The bit line voltage of the program inhibited NAND chain changes (in the second of a the two-step rise) by  $\Delta V_1$  in this period as it continues to rise to  $V_{DD}$  (**FIG. 8(F)**). This will allow the program inhibited NAND chain to float when the gate voltage SGD on the drain select transistor drops to  $V_{DD}$ . In the same period, the bit line voltage of the programming NAND chain is now allowed to float and is able to couple in  $\Delta V_2 = \alpha \Delta V_1$  (**FIG. 8(G)**) if one of its neighbors is in program inhibit mode.

**[0075]** (4) The drain word line connecting to the drain select transistors of a row of NAND chains has its voltage drop to  $V_{DD}$ . This will only float those program inhibited NAND chains where their bit line voltage is comparable to  $V_{DD}$ , since their drain select transistors are turned off (**FIGs. 8(B) & 8(F)**). As for the NAND chains containing a memory transistor to be programmed, their drain select transistors will not be turned off relative to the bit line voltage of near 0V at their drain. Also, as mentioned earlier, when a memory transistor to be programmed is next to one under program inhibition, its charge storage unit will have coupled in  $\Delta V_2$  due to the neighbor's boosted channel and charge storage unit.

**[0076]** (5) The memory transistors in a NAND chain not being addressed have their control gate voltage set to  $V_{PASS}$  to fully turn them on (**FIG. 8(C)**). Since a program inhibited NAND chain is floating, the high  $V_{PASS}$  and  $V_{PGM}$  applied to the unaddressed

memory transistors boost up the voltages at their channels and charge storage elements, thereby inhibiting programming.  $V_{PASS}$  is typically set to some intermediate voltage (e.g.  $\sim 10V$ ) relative to  $V_{PGM}$  (e.g.  $\sim 15-24V$ ). For a chain being program inhibited,  $V_{PASS}$  helps to reduce the effective  $V_{DS}$  for the cell subjected to the higher voltage  $V_{PGM}$ , thereby helping to reduce leakage. For a chain being programmed,  $V_{PASS}$  should ideally be at ground potential, thus an intermediate  $V_{PASS}$  voltage would be a reasonable compromise.

In the Program Phase:

[0077] (6) Programming voltage is applied to the control gate of a memory transistor selected for programming (**FIG. 8(D)**). The ones under program inhibition (i.e., with boosted channels and charge storage units) will not be programmed.

In the Discharge Phase:

[0078] (7) The various control lines and bit lines are allowed to discharge.

[0079] Basically, two types of boosting take place on a memory transistor to be programmed. The first is due to an adjacent memory transistor having a floated channel and charge storage unit capacitively boosted by a high control gate voltage from a word line. This occurs when a NAND chain is put into program inhibit mode. The first type of boosting due an adjacent program inhibit memory transistor, boosts the voltage on a charge storage unit of the memory transistor to be programmed. This is an undesirable side effect of program inhibition. The second is a compensatory adjustment on the bit line of the memory transistor to be programmed in order to offset the first boosting. By floating the bit line during some period when the voltage of a neighboring bit line is raised, the bit line acquires by capacitive coupling a boost in voltage to offset the effect of the first boosting.

[0080] In the first embodiment just described, the second compensatory bit line boosting occurs before the first boosting. This provides a maximum range of possible  $\Delta V_1$ . On the other hand, it also means that the bit line of the memory transistor to be programmed will become floated and its voltage susceptible to be moved by subsequent high programming voltages. However, it has been estimated that the bit line capacitance is considerably greater than the channel capacitance, and therefore, even if the bit line is floated, the bit line and channel voltage will not change much when a high programming

voltage appears on the control gate.

[0081] Alternatively, according to a second embodiment, the first boosting is started first, followed by the second boosting. In this way, any coupling to the floated bit line due to high programming voltage is minimized.

[0082] FIGs. 9(A)-9(G) are timing diagrams illustrating the voltage compensation scheme by capacitive bit line-bit line coupling during program operations, according to a second embodiment of the invention.

#### Bit Lines Precharge & Boosting Phase:

[0083] (1) The source select transistor is turned off by SGS at 0V (**FIG. 9(A)**) while the drain select transistor is turned on by SGD going high to  $V_{SG}$  (**FIG. 9(B)**), thereby allowing a bit line to access a NAND chain.

[0084] (2) The bit line voltage of a program inhibited NAND chain is raised (in the first of a two-step rise) to a predetermined voltage given by  $V_{DD} - \Delta V_1$  (**FIG. 9(F)**). This predetermined voltage is sufficient to cut off the drain of the NAND chain from its bit line when SGD drops to  $V_{DD}$  in (3), thereby floating the channels therein. At the same time, the bit line voltage of a programming NAND chain is fixed at 0V (**FIG. 9(G)**).

[0085] (3) The drain word line connecting to SGD of the control gates of the drain select transistors of a row of NAND chains has its voltage drop to  $V_{DD}$ . This will only float those program inhibited NAND chains where their drain select transistors are turned off because their bit line voltage is comparable to  $V_{DD}$  (**FIGs. 9(B) & 9(F)**). As for the NAND chains containing a memory transistor to be programmed, their drain select transistors will not be turned off relative to the bit line voltage of 0V at their drain.

[0086] (4) The memory transistors in a NAND chain not being addressed have their control gate voltage set to  $V_{PASS}$  to fully turn them on (**FIG. 9(C)**). Since a program inhibited NAND chain is floating, the high  $V_{PASS}$  and  $V_{PGM}$  applied to the unaddressed memory transistors boosts up the voltages at their channels and charge storage elements, thereby inhibiting programming.

In the Program Phase:

[0087] (5) The bit line voltage of the program inhibited NAND chain changes (in the second of a the two-step rise) by  $\Delta V_1$  in this period as it continue to rise to  $V_{DD}$  (**FIG. 9(F)**). In the same period, the bit line voltage of the programming NAND chain is now allowed to float and is able to couple in  $\Delta V_2 = \alpha \Delta V_1$  (**FIG. 9(G)**) if one of its neighbors is in program inhibit mode.

[0088] Programming voltage is applied to the control gate of a memory transistor selected for programming (**FIG. 9(D)**). The ones under program inhibition (i.e., with boosted channels and charge storage units) will not be programmed.

In the Discharge Phase:

[0089] (6) The various control lines and bit lines are allowed to discharge.

[0090] **FIG. 10** is a flow diagram showing a method of programming a page of contiguous memory storage units while minimizing the coupling errors due to individual memory transistors among them being program inhibited or locked out, according to one preferred embodiment.

#### All-bit Programming

[0091] **STEP 400:** For a page of contiguous memory storage units, each unit having a charge storage unit between a control gate and a channel region defined by a source and a drain, providing a bit line switchably coupled to the drain of each unit and a word line coupled to all the control gates of said page of memory storage units.

#### Bit line Precharge

[0092] **STEP 410:** Applying an initial, first predetermined voltage to the bit lines of designated memory storage units of the page to enable programming.

[0093] **STEP 420:** Applying an initial, second predetermined voltage to the bit lines of un-designated memory storage units of the page to be program inhibited.

[0094] **STEP 430:** Floating the program-enabled bit lines, while raising the program-inhibited bit lines from said second predetermined voltage by a predetermined voltage

difference to a third predetermined voltage, wherein a predetermined portion of the predetermined voltage difference is coupled as an offset to any neighboring, floated, program-enabled bit lines, and said third predetermined voltage enables floating of the channel of each program-inhibited memory storage unit.

#### Program Pulsing, Verifying & Inhibiting

[0095] **STEP 440:** Applying a programming voltage pulse to the word line in order to program the designated memory storage units of the page, wherein those un-designated memory storage units of the page are program- inhibited by virtue of their floated channel boosted to a program inhibited voltage condition, and a perturbation resulted from the boosting on any neighboring program-enabled memory storage units is compensated by said offset.

[0096] **STEP 450:** Verifying the **selected** memory storage units under programming.

[0097] **STEP 460:** Re-designating any memory storage units that have not been verified.

[0098] **STEP 470:** Are all **memory** storage units of the page verified? If not, return to **STEP 420**. If so, proceed to **STEP 480**.

[0099] **STEP 480:** End.

[0100] **FIG. 11** is a flow diagram showing a method of programming a page of contiguous memory storage units while minimizing the coupling errors due to individual memory transistors among them being program inhibited or locked out, according to another preferred embodiment. This embodiment is similar to that shown in **FIG. 10**, except in the steps for Precharge with Perturb Offset, the boosting the channel step precedes the floating the bit line steps.

#### Bit line Precharge

[0101] **STEP 410':** **Applying** an initial, first predetermined voltage to the bit lines of designated memory storage units of the page to enable programming.

[0102] **STEP 420':** Applying an initial, second predetermined voltage to the bit lines of un-designated memory storage units of the page to be program inhibited, said second



predetermined voltage enables floating of the bit line and channel of each program-inhibited memory storage unit.

[0103] **STEP 430'**: **Floating** the program-enabled bit lines, while raising the program-inhibited bit lines from said second predetermined voltage by a predetermined voltage difference to a third predetermined voltage, wherein a predetermined portion of the predetermined voltage difference is coupled as an offset to any neighboring, floated, program-enabled bit lines, and said third predetermined voltage enables floating of the channel of each program-inhibited memory storage unit.

[0104] **FIG. 12** illustrates a preferred sense module implementing the various aspects of the present invention. The sense module 380 comprises a bit line isolation transistor 502, a bit line pull down circuit 520, a bit line voltage clamp 610, a readout bus transfer gate 530 and a sense amplifier 600.

[0105] A similar **sense** module is disclosed in co-pending and co-owned United States Patent Application, entitled "Non-volatile memory and method with improved sensing" filed by Adrian-Raul Cernea and Yan Li on the same day as the present application. The entire disclosure of said co-pending application is hereby incorporated herein by reference.

[0106] In general, a page of memory cells are operated on in parallel. Therefore a corresponding **number** of sense modules are in operation in parallel. In one embodiment, a page controller 540 expediently provides control and timing signals to the sense modules operated in parallel.

[0107] The sense module 380 is connectable to the bit line 36 of a memory cell 10 when the bit line isolation **transistor** 502 is enabled by a signal BLS. The sense module 380 senses the conduction current of the memory cell 10 by means of the sense amplifier 600 and latches the read result as a digital voltage level SEN2 at a sense node 501 and outputs it to a readout bus 532.

[0108] The sense amplifier 600 essentially comprises a second voltage clamp 620, a precharge circuit **640**, a discriminator or compare circuit 650 and a latch 660. The discriminator circuit 650 includes a dedicated capacitor 652.

[0109] One feature of the sense module 380 is the incorporation of a constant voltage supply to the bit line **during** sensing. This is preferably implemented by the bit line voltage clamp 610. The bit line voltage clamp 610 operates like a diode clamp with a transistor 612 in series with the bit line 36. Its gate is biased to a constant voltage BLC equal to the desired bit line voltage  $V_{BL}$  above its threshold voltage  $V_T$ . In this way, it isolates the bit line from the sense node 501 and sets a constant voltage level for the bit line, such as the desired  $V_{BL} = 0.5$  to  $0.7$  volts during program-verifying or reading. In general the bit line voltage level is set to a level such that it is sufficiently low to avoid a long precharge time, yet sufficiently high to avoid ground noise and other factors.

[0110] The sense amplifier 600 senses the conduction current through the sense node 501 and determines whether the conduction current is above or below a predetermined value. The sense amplifier **outputs** the sensed result in a digital form as the signal SEN2 at the sense node 501 to the readout bus 532.

[0111] The digital control signal INV, which is essentially an inverted state of the signal SEN2, is also output to **control** the pull down circuit 520. When the sensed conduction current is higher than the predetermined value, INV will be HIGH and SEN2 will be LOW. This result is reinforced by the pull down circuit 520. The pull down circuit 520 includes an n-transistor 522 controlled by the control signal INV and another n-transistor 550 controlled by the control signal GRS. The GRS signal basically allows the bit line 36 to be floated when its goes LOW regardless of the state of the INV signal. During programming, the GRS signal goes HIGH to allow the bit line 36 to be pulled to ground. When the bit line is required to be floated, the GRS signal goes LOW.

[0112] **FIGs. 8(H)-8(O)** illustrates the timing of the preferred sense module shown in **FIG. 12** in relation to the features of the present invention. Detailed description of the operation of the preferred sense module in regards to other inventive features has been described and claimed in co-pending and co-owned United States Patent Application Serial Number, 10/254830 filed on September 24, 2002 by Adrian-Raul Cernea and Yan Li. The entire disclosure of the referenced application is hereby incorporated herein by reference.

ALTERNATIVE EMBODIMENT WITH CORRECTION WHEN BOTH NEIGHBORS  
ARE LOCKED OUT

[0113] As described earlier, when a memory cell in a NAND chain is under programming, its bit line and therefore its channel is kept around ground potential. When a high programming voltage appears on the control gate of the memory cell, it induces a high voltage on its floating gate. The channel being kept around ground potential helps to maximize the potential difference between the channel and the floating gate, thereby creating a favorable condition for tunneling electrons transferring therebetween to effect programming.

[0114] For those NAND chains on the same set of word lines that no longer need programming, they are program inhibited or locked out in spite of being subjected to programming voltages on their control gates. This is accomplished by reducing the tunneling potential. The NAND chain to be program inhibit has its bit line raised from ground to  $V_{DD}$ . This effectively turns off the drain select transistor and floats the channel of the NAND chain. As the channel is floated, it will rise from ground to a higher voltage because of the high programming voltages appear on the word lines. This reduces the tunneling potential between the associated floating gate and the channel to inhibit programming.

[0115] Thus, a gross scheme is to ground the channel of a NAND chain to create a favorable condition for programming and to float the channel for inhibiting programming. However, as pointed out earlier, a NAND chain under programming is perturbed by the high potential on the channel of one or both of its neighbors if they are in program inhibit mode. The scheme described earlier compensates this perturbation by attempting to adjust the bit line voltage of the NAND chain under programming by the same amount in a sort of “common-mode” cancellation. The adjustment is accomplished by floating the bit line from ground and capacitively coupling a portion of the neighboring bit line voltage when it transits from zero to  $V_{DD}$ . When a programming NAND chain has both its neighbors in program inhibit mode, there will be capacitive coupling contributions from the bit line of both neighbors.

[0116] FIG. 13 illustrates a programming configuration along a row of NAND chains where a second order error may still occur. This occurs when a NAND chain 50 under

programming is flanked by two adjacent chains 51, 51' also under programming and further flanked by two next-to-adjacent chains 52, 52' that are in program inhibit mode. The scheme described above calls for the chains under programming 50, 51, and 51' to have their bit lines 36-0, 36-1, 36-1' floated and capacitively coupled from ground a voltage from their neighboring bit lines. This is fine for the adjacent chains 51, 51' as the additional coupled voltage  $\Delta V_1$  is used to compensate for the perturbation due to the boosted channels of the next-to adjacent chains 52, 52'. However, for the NAND chain 50 flanked by the adjacent chains 51, 51', its channel voltage should ideally be at ground to provide maximum programming efficiency. If its bit line 36-0 is also floated from ground it will acquire an additional, non-zero voltage  $\Delta V_0$ , coupled from a portion of the additional voltage  $\Delta V_1$  from the bit lines 36-1, 36-1' of the adjacent chains.

[0117] According to another aspect of the invention, when a cell of a NAND chain is under programming and the NAND chain is flanked by two adjacent neighbors also under programming, the bit line coupled to the NAND chain is forced to a voltage so as to maximize the potential difference between the cell's floating gate and channel. In a preferred embodiment, this would require the bit line to be set to ground potential. This will require the NAND chain to be cognizant of the state of its neighbors, i.e., whether they are in program or program inhibit modes.

[0118] In a preferred embodiment, a sense module such as the sense module 380 shown in FIG. 12 controls the voltage on the bit line. As described earlier, the sense module 380 and in particular the sense amplifier 600 coupled to the bit line 36 generates a control signal **INV** that is **HIGH** when in program mode and **LOW** when in program inhibit mode. Thus the signal **INV** can be used to indicate to a neighbor whether the NAND chain coupled to the bit line 36 is in program or program inhibit mode.

[0119] FIG. 14 illustrates a sense module configuration in which each sense module also senses the **INV** signal of its neighbors. The bit line 36-0 is flanked by the bit lines 36-1 and 36-1' respectively. The sense module 380-0 is coupled to the bit line 36-0 and the sense modules 380-1 and 380-1' are respectively coupled to the bit line 36-1 and 36-1'. Since each sense module receives the **INV** signals from its adjacent neighbors, the sense module 380-0 receives the **INV** signal from the sense module 380-1 and 380-1' respectively as input signals  $INV_L$  and  $INV_R$ . Similarly the **INV** signal of the sense module 380-0 is input to the sense modules 380-1 and 380-1'.

[0120] **FIG. 12** illustrates a sense module responsive to the neighboring states for pulling down the bit line to ground, according a preferred embodiment. This is implemented by an optional bit line pull-down circuit 560 for pulling down the node 523 to ground depending on the neighboring states. When the NAND chain coupled to the bit line 36 is in program mode, INV is HIGH, and the transistor 522 is conducting so that the bit line is coupled to the node 523. The bit line pull-down circuit includes two n-transistors connected in series to ground. The conduction of the two n-transistors are controlled by the INV signals  $INV_L$  and  $INV_R$  input from the neighboring sense modules 380' and 380'' respectively. When both neighbors are in program mode, both  $INV_L$  and  $INV_R$  will also be HIGH, thereby pulling the node 523 and therefore the bit line 36 to ground. Conversely, if one or more of the neighbors are in program inhibit mode, the node 523 will not be pulled to ground by the circuit 560.

[0121] **FIG. 15** illustrates an alternative implementation in which the signal indicating whether a neighbor is in program or program inhibit mode is derived directly from the state of the neighbor's bit line. This scheme is useful when the signal is not readily available from a neighboring sense module. As described earlier, when a NAND chain is in program mode, its bit line voltage is kept around ground potential and when it is in program inhibit mode, its bit line voltage is kept at  $V_{DD}$ .

[0122] A virtual INV signal generator 570 senses the bit line voltage and outputs a virtual INV signal, VINV, which is logically equivalent to the INV signal generated by a sense module. The virtual INV signal generator 570 comprises a p-transistor 572 in series with an n-transistor 574 in a pull up/down configuration for the node that outputs the signal VINV. The p-transistor 572 is weakly pulled up by a voltage  $V_{WKP}$  at its gate. The voltage of the bit line 36' is input to the gate of the n-transistor 574. The virtual INV signal generator 570 essentially behaves like a tri-state inverter that outputs a HIGH VINV signal when the bit line 36-1 has a voltage close to ground (program mode) and outputs a LOW VINV signal when the voltage is at  $V_{DD}$  (program inhibit mode.)

[0123] In the example shown in **FIG. 15**, the VINV signal is input as the signal  $VINV_L$  to the neighboring sense module 380-0. Thus, using either the signal INV or VINV, information about the programming or program inhibiting state is communicated to the sense module 380-0 coupled to a NAND chain. In the case when both of its neighboring

NAND Chains are in a program mode, the sense module 380-0 pulls down the bit line to ground by way of the bit line pull-down circuit 560.

[0124] Although the various aspects of the present invention have been described with respect to certain embodiments, it is understood that the invention is entitled to protection within the full scope of the appended claims.